The PEM Fuel Cell System with DC/DC Boost Converter: Design, Modeling and Simulation

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***Abstract*—The fuel cells are considered as one of the most promising devices for standalone/grid connected distributed generations (DGs) due to its cleanliness, modularity and higher potential capability. The barriers in the widespread use of fuel cells are their slow response for sudden load changes and higher installation cost. In this paper a simulation study of dynamic behavior of Nexa^{TM} 1.2kW PEM fuel cell with DC/DC boost converter is carried out for compact design of PCU. The necessity for the requirement of boost converter compared with cascaded two stack fuel cell model is also addressed. Moreover the performance of the simple DC/DC boost converter as power modulator for Nexa^{TM} 1.2kW PEM fuel cell model is analyzed for varying loads in order to control power flow for enhanced performance.**

***Index Terms*—DC/DC Converter, Distributed generation, PEM fuel cell, PI controller.**

I. Introduction

The availability of existing central power generation is not sufficient to meet the growing energy demands. Many private sectors invest huge money to meet out their contingent loads under power cut and also to cater peak load demand locally using conventional diesel generators. The use of conventional means of power sources are getting limited due to their inefficient and untidy operation. The Private sectors and Utilities are now concentrating on green power technologies with accrued benefits on account of their cleanliness, modularity, high efficiency & reliability. Among the different green power technologies e.g. wind power, photovoltaic, micro turbine, & fuel cells, the fuel cell based distributed generation is considered as one of the most promising technology due to high operating efficiency (40-60%), reliability and higher potential capability [1],[2]. The Distributed Generation in fact offers enhanced voltage support, reduced transmission & distribution losses, improved reliability & power quality [3]. The fuel cell based distributed generation can be placed anywhere in the system to upgrade system integrity, reliability and efficiency.

The PEM fuel cell technology is the best candidate for residential and commercial applications due to low operating temperature, quick start up and high power density [4]. The open circuit voltage of the single cell is in the range of 0.8-1.2V. To get higher operating voltage & power; many such cells are stacked and connected in the form of cascaded series & parallel connection. Normally the fuel cell stack available in the market gives operating voltage in the range of 26V to 50V. These stacks are now widely used in portable devices, automotive industry, residential and stationary power needs but unsuitable for abrupt load changes due to slow response of underlying electrochemical and thermodynamic processes.

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In literature [5]-[7], many fuel cell models are developed based on underlying thermodynamic and electrochemical equations. How ever in most of the models the effect of change in temperatures and fuel pressures is not taken into account. As the fuel pressure or temperature increases the power density of the fuel cell stack also goes up for increasing loads [8], [9]. In reality, the fuel cell variants differ in terms of characteristics, materials, construction and their application suitability. To get better understanding of the characteristics and responses of fuel cell in a system, an accurate desktop fuel cell model needs to be developed in order to design efficient & accurate power electronics interface. Apart from the models based on Thermodynamic and electrochemical equations, an improved parametric model based on circuit simulator PSpice for a class of PEM fuel cell is also developed to analyze its dynamic behavior for changes against temperature [10].

The DC-DC Converter is an integral part of fuel cell power conditioning unit, it is therefore this paper intends to present modeling of fuel cell as well as of DC/DC Converter. The design of DC/DC converter and their controller plays an important role to control power regulation particularly for a common DC bus. The boost converter offers higher efficiency and less component counts compared to other DC/DC converters topologies like push pull, half bride and full bridge etc. which could possibly be used to interface fuel cell system to the load. Several such topologies of DC/DC converters based on their components count, advantages & disadvantages are discussed and compared [11].

If the available fuel cell generation is not sufficient to meet the sustainable load demand, there is a need of additional energy storage device such as battery, capacitors and ultra capacitors to meet the peak power demands. Among these energy storage devices, the ultra capacitors can be placed at the dc link without any additional circuits because it has long life and maintenance free. But an energy storage e.g. Battery requires additional control circuit for the bidirectional DC/DC power flow operations during charging and discharging conditions. This increases the cost of the system and reduces life span and reliability. The comparison of battery vs ultra capacitor is also reported

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in the literature [12].

This paper intends to study the fuel cell terminal voltage regulating characteristics and its dynamic limitations under varying loads condition. The paper is organized as: the section II discusses the dynamic behavior of Nexa[TM] 1.2kW PEM fuel cell model. The section III details out the design of a simple DC/DC boost converter used to provide a regulated voltage for varying loads and the section IV evaluates the performance of PEM fuel cell system with DC/DC boost converter using simulink and simulation results is brought out.

II. PEM Fuel Cell Model

A fuel cell is a static energy conversion device that converts chemical reaction of fuels directly into electrical energy with some heat and produces water as its byproduct [13]. The chemical reaction sustains as long as fuel and oxidant supply is maintained. Fig. 1 shows a simple arrangement of fuel cell system. The chemical reaction involved in the anode, cathode and electrolyte membrane for the production of electricity is given below:

$$\text{Anode reaction} \qquad H_2 \Rightarrow 2H^+ + 2e^- \tag{1}$$

$$\text{Cathode reaction} \qquad {}^1\!/_2 O_2 + 2H^+ + 2e^- \Rightarrow H_2O \tag{2}$$

$$\text{Overall reaction} \qquad H_2 + {}^1\!/_2 O_2 \Rightarrow H_2O \tag{3}$$

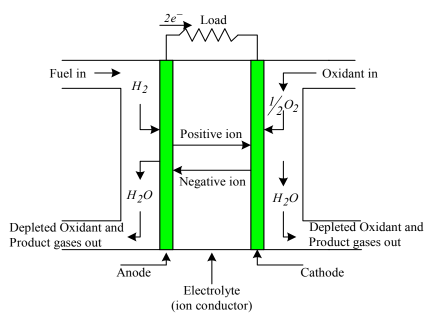

Fig. 1. Fuel cell operation diagram.

The fuel cell performance is earmarked by its thermal and electrical efficiency. The thermodynamic efficiency depends on fuel processing, water management and temperature control of the system. The electrical efficiency of the fuel cell depends on the activation & concentration loss apart from natural Ohmic loss. The fuel cell stack voltage under loaded condition (V_{dc_stack}) is a function of activation loss (V_{act}), concentration loss (V_{con}), and ohmic loss (V_{ohmic}) and is given by Nernst equation [14]:

$$V_{dc\_stack} = V_{open} - V_{ohmic} - V_{act} - V_{con} \tag{4}$$

$$V_{open} = N_o \cdot \left[V_o + \frac{RT}{2F} ln\left(\frac{PH_2 \sqrt{PO_2}}{PH_2O\sqrt{PO}} \right) \right] \tag{5}$$

$$V_{ohmic} = I_{dc} . R_{FC} \tag{6}$$

$$V_{act} = N_o \cdot \frac{RT}{2\alpha F} . ln\left(\frac{I_{dc}}{I_0} \right) \tag{7}$$

$$V_{con} = -c.ln\left(1 - \frac{I_{dc}}{I_{Lim}} \right) \tag{8}$$

Fig. 2 shows the simulink model as developed for the fuel cell stack based on the above five equations (4)-(8). The simulated I-V characteristics of PEM fuel cell stack voltage for the fixed values of input fuel pressures for single cell is shown in Fig. 3. It can be seen that at low current level, the ohmic loss becomes less significant and the increase in output voltage is mainly due to activity of slowness of chemical reactions. So this region is also called *active* polarization. At very high current density the voltage fall down significantly because of the reduction of gas exchange efficiency. This is mainly due to over flooding of water in catalyst and this region is also called *concentration* polarization. Intermediate between the active region and concentrations region there is a linear slope which is mainly due to internal resistance offered by various components of the fuel cell. This region is generally called as *ohmic* region [10], [15].

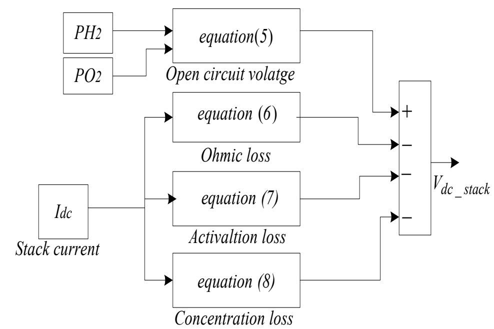

Fig. 2. Dynamic model of PEMFC using MATLAB/Simulink.

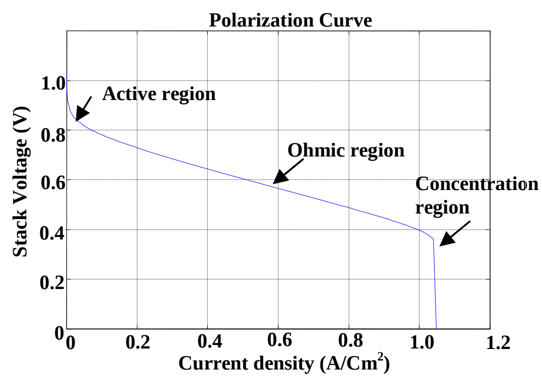

Fig. 3. I-V Characteristics curve of PEM fuel cell single stack.

Fig. 4 shows the measured output characteristics of the Nexa[TM] 1.2kW PEM fuel cell model [16]. It is observed that the simulated characteristic curve is almost same as experimental results. The fuel cell output voltage can be operated safely in the linear range of voltages from 26V to 36V and the stack currents also varied from 10A to 45A for constant hydrogen input fuel supply. The linearized output voltage due to its ohmic nature is given by:

$$V_{fc\_lin} = V_{0\_lin} - R_{in\_lin} I_{fc} \tag{9}$$

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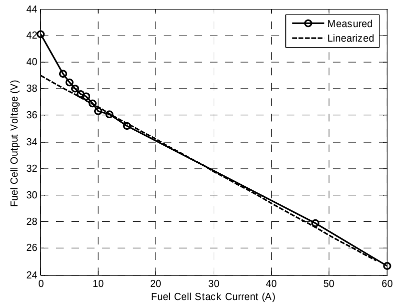

Fig. 4. Measured Output Characteristics of the Nexa TM

The Fig. 5 shows the I-V characteristics of PEM fuel cell for 2 stacks. It is observed that the fuel cell can be operated safely in the linear range of voltages from 40V to 71V as compared to its operation from 26V to 36V (for single stack) with almost double power for same current as compared to single stack operation. But the cost of the two stack fuel cell has also increased two fold. Therefore in this paper a simple DC/DC boost converter is used to boost the output voltage of the fuel cell system due to its superiority of higher efficiency and simplicity in control.

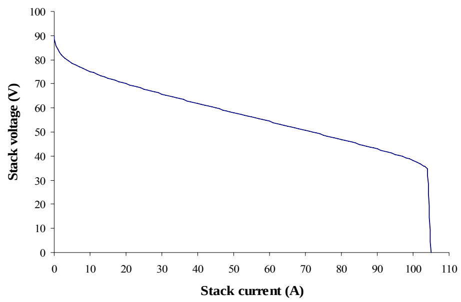

Fig. 5. I-V characteristic curve of PEM fuel cell for 2 stacks.

III. Power Electronic Interface

A. Design of DC/DC Boost Converter

Looking into the drooping characteristics curve, the unregulated terminal voltage cannot be directly interfaced to the DC bus or by using DC/AC inverters for residential/grid applications. Therefore for converter design, a linear region operation (due to resistance offered by internal components) of the fuel cell stack is only taken into account. Beyond the linear region, the fuel cells can not be operated as electrolyte membrane of the cell may get damaged. Fig. 6 shows a closed loop continuous conduction mode operation of PWM DC/DC boost converter.

The main advantages of the boost converter are higher efficiency & reduced component count and it converts the unregulated voltage into desired regulated voltage by varying the duty cycle at high switching frequency lowering the size and cost of energy storage components. The selection of components like boost inductor value and capacitor value is very important to reduce the ripple generation for a given switching frequency. However large inductance tends to increase the start-up time slightly while small inductance allow the coil current to ramp up to higher levels before switch turns off [17]. Fig.7 and Fig.8 shows the equivalent circuit of the dc/dc boost converter during switch on time and off time [18]. Equations from (10) to (14) shows the voltage drop across the inductor during the on and off period of converter in steady state conditions.

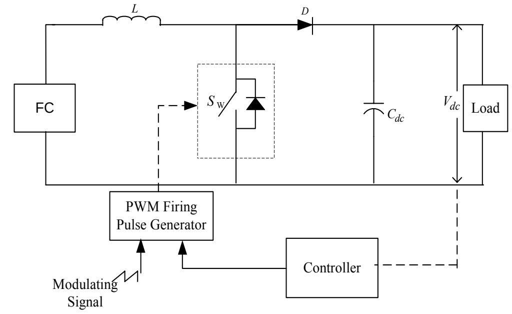

Fig. 6. Typical structure of DC-DC boost converter with feedback control.

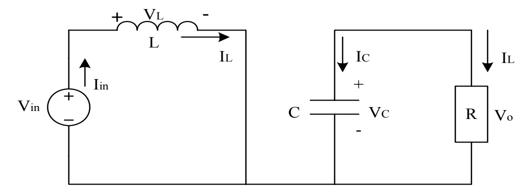

Fig. 7. Equivalent circuit of the DC/DC boost converter during switch on time.

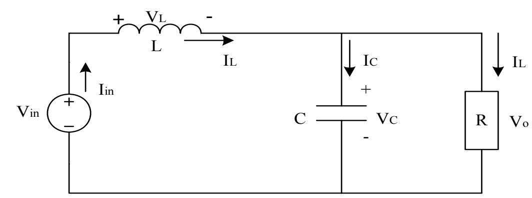

Fig. 8. Equivalent circuit of the DC/DC boost converter during switch off time.

$$i_L(t) = \frac{1}{L} V_{in} t + I_L(0) \qquad 0 \le t \ge dT \qquad (10)$$

$$i_L(t) = \frac{1}{L}\left(V_{in} - V_o\right)\left(t - dT\right) + I_L dT \qquad dT \le t \ge T \qquad (11)$$

Assuming $I_L(t)=I_L(0)$, at $t=dT$ and $t=T$, from the above equations

$$\frac{V_o}{V_{in}} = \frac{T_s}{t_{off}} = \frac{1}{1-d} \qquad (12)$$

For lossless circuit,

$$V_{in} I_{in} = V_o I_o \qquad (13)$$

$$\frac{I_o}{I_{in}} = 1 - d \qquad (14)$$

The gain of the boost converter considering internal source resistance is given by:

$$\frac{V_o}{V_{in}} = \frac{1}{(1-d) + \dfrac{R_{fc}}{(1-d)R_L}} \qquad (15)$$

The size of the reactive elements of Boost converter can be determined from the rated voltage, current ripple, voltage ripple and switching frequency of the converter based on the equations from (15) to (18). Table I enlists the main components of inductor and capacitor values for

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Nexa[TM] *1.2kW PEM fuel cell.*

$$d = \frac{V_{in}}{V_{out}} \tag{16}$$

$$Current\ Ripple = \frac{d(1-d)^2 RT_s}{L} \tag{17}$$

$$Voltage\ Ripple = \frac{dT_s}{RC} \tag{18}$$

TABLE I
BOOST CONVERTER PARAMETERS

Parameters	Values
Current ripple	3%
Voltage ripple	0.5%
L	$4.8mH$
C	$1200\mu F$
Fs	$20KHz$

B. Control Strategy

In this work a simple feedback PI controller is used to maintain a constant bus voltage of 80V in converter output, irrespective of variations in load and fuel cell terminal voltage. The PI controller minimizes steady state error to zero. The process of sensing the control variable and the transformation of dimensionless measured quantities ($V_o^d(t)$, $V_{fc}^d(t)$, $I_o^d(t)$) compared with reference signals are shown in Fig.9 [19]. The change in duty cycles for varying load is obtained by optimizing the suitable PI parameter values of the voltage controller and current controller.

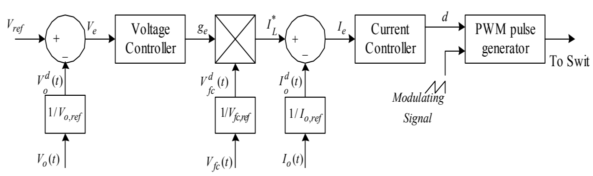

Fig. 9 Closed loop control block for PWM pulse generator.

IV. SIMULATION RESULTS

From the above discussion it is observed that the single stack fuel cells can be operated with in the permissible range of 26V to 36V for constant fuel input to maintain the stability of the system. To regulate the fuel cell output voltages and to improve the performance of the FC system, a simple boost converter interfaced with PEM fuel cell is simulated in MATLAB/Simulink environment. Fig.10 shows changes in fuel cell terminal voltage and current for varying loads. It is observed that for load changes from 600W to 1100W instantaneously, the fuel cell voltage and current takes about 50ms to 70ms to reach a new steady state. Fig. 11 demonstrates the effect of the power control and dc link voltage for the changes in load current approximately from 20A to 44A.

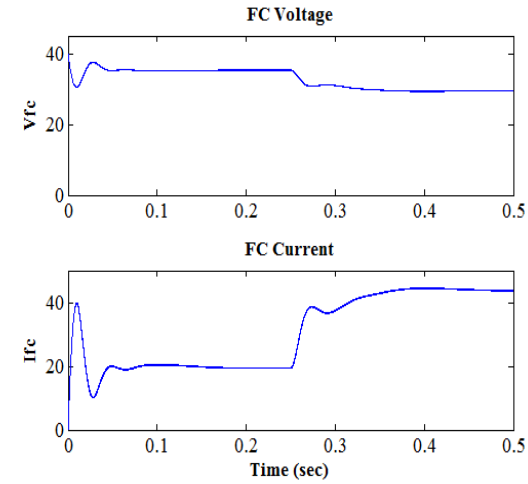

Fig. 10. Fuel cell terminal voltage and current for changes in load.

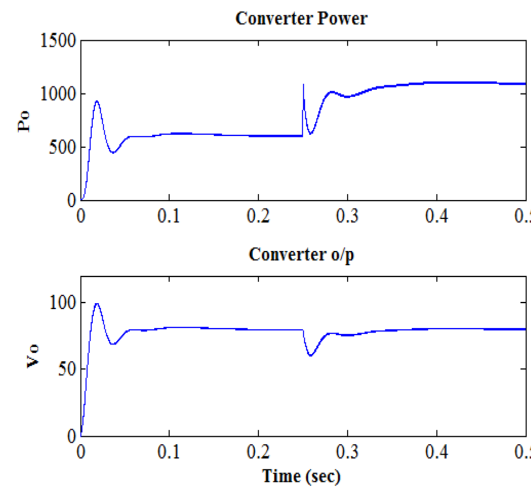

Fig. 11. Converter output power and voltage for changes in load.

It is observed that the design of simple boost converter with PI controller gives better performance for changes in load without the use of any storage devices. Hence, for low power applications the design of simple boost converter gives better performance for standalone/grid connected applications. However the usage of backup energy storage devices like batteries, capacitors and ultra capacitor banks plays an important role to protect the FC system during start up.

V. CONCLUSION

This paper presents a study of dynamic behavior of 1.2kW Nexa[TM] PEM fuel cell. The dynamic limitations of the single stack and double stack fuel cell model are analyzed based on their dynamic behavior of characteristic curves. To regulate the fuel cell terminal voltages a simple DC/DC boost converter is interfaced with PEM fuel cell system. It is observed that the design of simple DC/DC boost converter gives better performance for varying loads thereby increasing its life span. The optimized parameters of PI controllers gives better response curve to control the power flow through Fuel Cells.

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APPENDIX

N_O	Cell Number
Vo	Open cell voltage
R	Universal gas constant
T	Temperature of the fuel cell stack
F	Faraday's constant
PH_2	Hydrogen partial pressure
PO_2	Oxygen partial pressure
PH_2O	Water partial pressure
PO	Standard pressure in the pressure units
A	Charge transfer coefficients of the electrodes
I_{dc}	Current of the fuel cell stack
I_{Lim}	Limiting current of FC stack
I_o	Exchange current of FC stack
C	Empirical coefficient for concentration voltage
V_{fc_lin}	Linearized output voltage,
V_{0_lin}	Linearized voltage without the load,
R_{in_lin}	Linearized internal resistance
I_{fc}	Fuel cell current.
d	Duty ratio
V_{in}	Input voltage
V_{out}	Output voltage (v)
R	Load resistance (Ω)
C	Capacitance (F),
L	Inductor (H)
T_s	Switching time of firing pulses.

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